# *Preliminary Change Request for including chromaticity sextupoles in the SNS accumulator ring*

BNL/SNS TECHNICAL NOTE

NO. 093



Y. Papaphilippou , N. Tsoupas, Y.Y. Lee and J. Wei

April 6, 2001

COLLIDER-ACCELERATOR DEPARTMENT
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

# Preliminary Change Request for including chromaticity sextupoles in the SNS accumulator ring

Y. Papaphilippou, N. Tsoupas, Y.Y. Lee and J. Wei
Brookhaven National Laboratory, Upton NY, USA

April, 6 2000

**Abstract**

In view of the adopted design changes for SNS accumulator ring [1], complementary studies have been undertaken, in order to justify the need of high-field chromatic sextupoles for chromaticity correction.

## 1 The SNS accumulator ring lattice

The SNS accumulator ring has a hybrid lattice design consisting of four identical arcs and straight sections. The arc has a FODO structure, with four cells (8 quadrupoles and dipoles) plus a quadrupole that matches the arcs with the straight sections. The later contains two quadrupole doublets, setting the total number of quadrupoles at 52. The magnetic elements are placed and powered in a way to preserve a four-fold symmetry. A schematic presentation of one super-period is presented in Fig. 1. The lattice has been matched for several working points. The optical functions for the nominal working point (6.3,5.8) are shown in Fig. 2.

In the proposed lattice design, five chromatic sextupoles are placed downstream (SVX3, SVX4) or upstream (SVX5, SVX6, SVX7) to the arc quadrupoles, at areas of large dispersion (Figs. 1 and 2). These "strong" sextupoles have been foreseen for adjusting the chromaticities to desired values, minimizing off-momentum optical mismatch and control resonance effects and instabilities [2].

We present in this note the studies undertaken in order to justify the need of four families of chromatic sextupoles. We estimate the impact in the lattice functions and non-linear dynamics and show the benefit with respect to the machine performance.

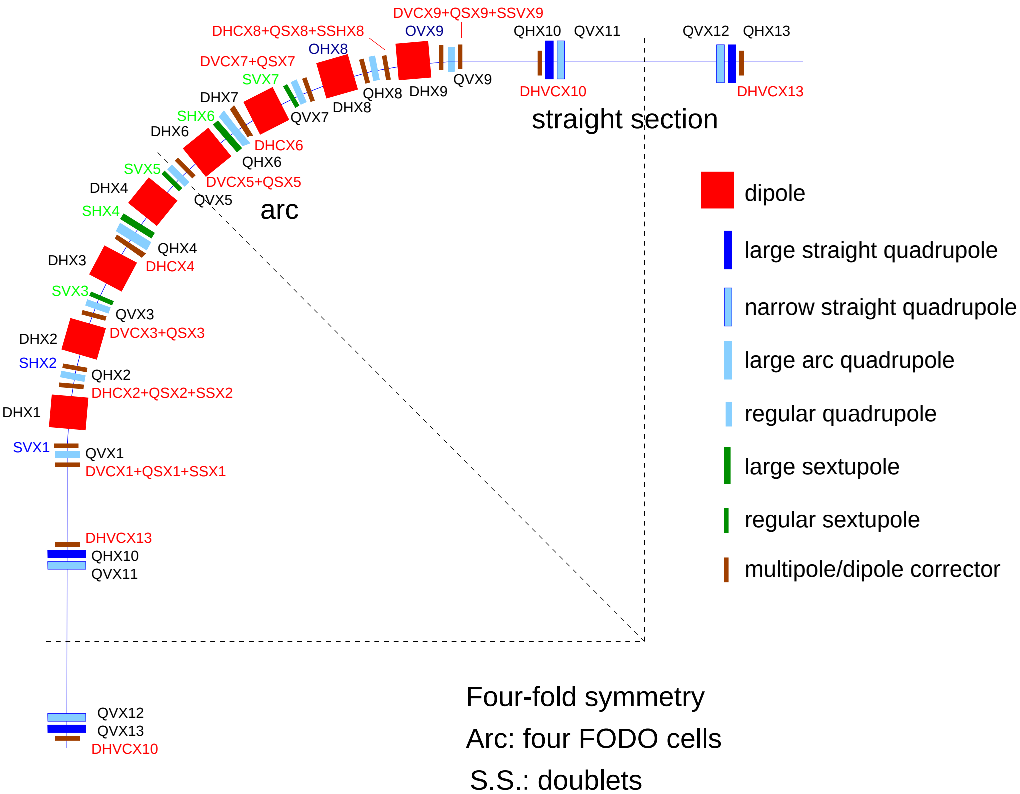


Figure 1: Schematic layout showing dipole, quadrupole, sextupole, and corrector magnets of one lattice super-period. The chromatic sextupoles are shown in green.

# 2 Justification of Changes

## 2.1 Optical matching

One of the design aspects that will help avoiding beam resonances and/or beam instabilities, thereby minimizing the beam losses in the accumulator ring, is the chromaticity control. Without this control, the tune spread produced by the natural chromaticity is about $\pm 0.08$, similar to the spread produced by the space-charge. The adjustment of the chromaticity and the optical compensation can be achieved by using chromaticity sextupoles. The SNS lattice contains five 15 cm long chromatic sextupoles per super-period. Their design parameters (see [1]) are presented in Table 2.1.

Two families of sextupoles, placed at high-beta and high-dispersion regions, can control the linear chromaticity of the ring. The sextupoles however may strongly affect the first and second order of the beta and dispersion functions dependence on the momentum spread, introducing strong "beta/dispersion waves" and, thereby, reducing the dynamic aperture. In addition, this beta/dispersion variation will increase the first and higher order terms of the chromaticity. This is clearly shown in figure 3: with a two-family scheme, the optical distortion in $\beta$-function is as large as 30% for off-momentum orbits.

In order to minimize the dependence of the beta, the dispersion functions and the chro-

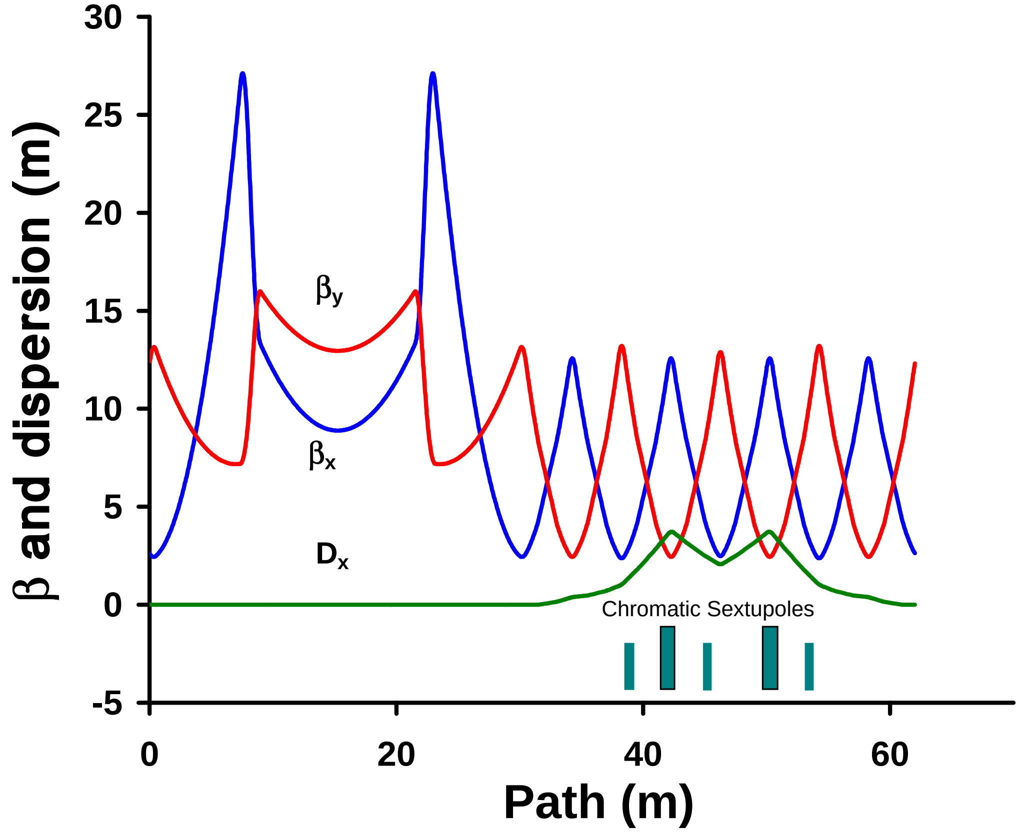


Figure 2: Lattice functions of one lattice super-period consisting of a FODO arc and a doublet straight. The horizontal phase advance across the arc section is $2\pi$ radian. The dispersion in the straight section is zero.

maticity on $\delta p/p$, additional families of sextupoles are required. In the proposed chromaticity correction scheme, three of the sextupoles are powered independently and two of them in series, forming a total of four families. With a four-family scheme, the off-momentum optics is greatly improved, and the $\beta$-wave is minimal (Fig. 4).

By using the HARMON module of the MAD program [4], we have computed the required strength of the four families of sextupoles in order to adjust the horizontal and vertical chromaticity $\xi_{x,y}$ to a wide value range and at the same time to minimize the optics functions' perturbation (Fig. 5). We observe that the sextupole strengths for the most extreme cases are less than 3 m$^{-3}$. Thus, the strength requirements of 4.15 m$^{-3}$, given in Table 2.1, are sufficient to handle the chromaticity/optics control, leaving a comfortable 20% margin.

## 2.2 Non-linear dynamics

### 2.2.1 Frequency maps and Dynamic aperture

Additional non-linear dynamic have shown the beneficial effect of the chromatic sextupoles. In Figs. 6, we display frequency maps [5, 6], for the working point (6.3,5.8). The maps are

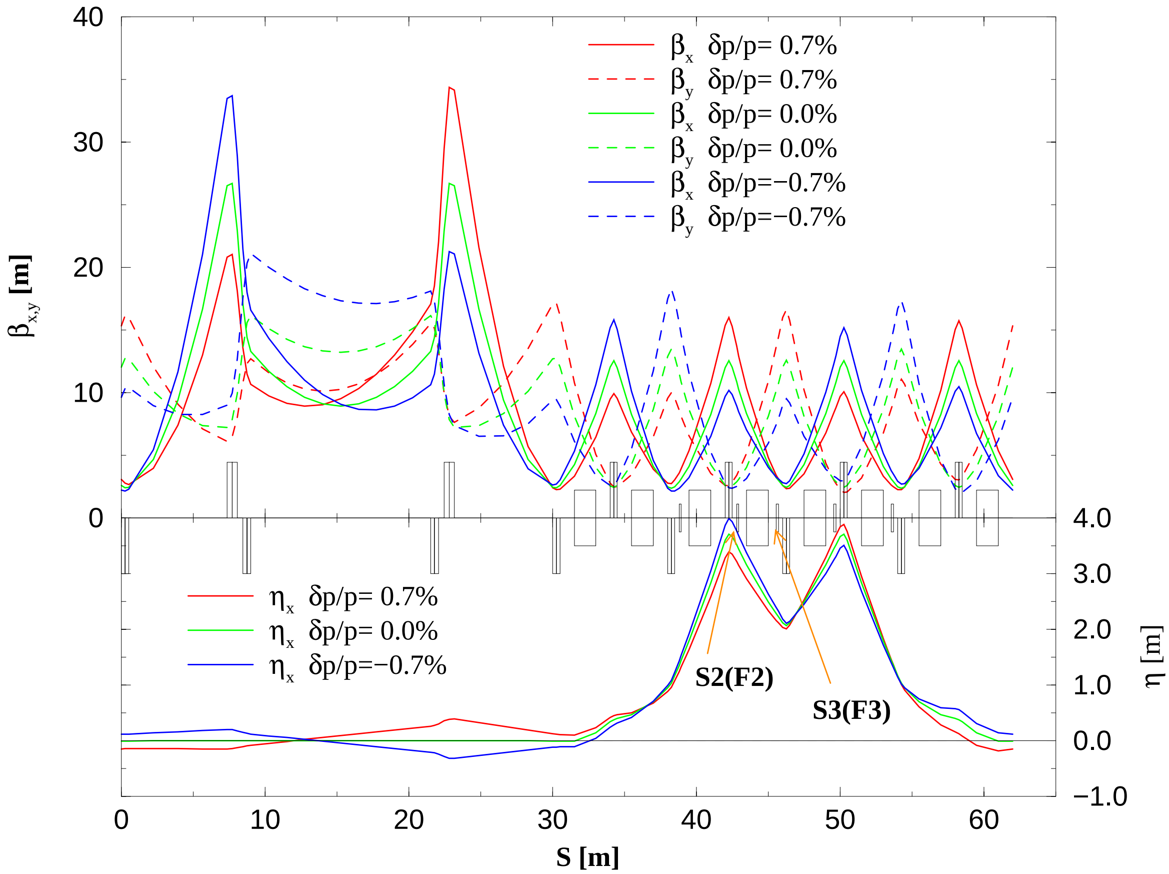


Figure 3: Lattice functions of the SNS accumulator ring for the nominal tunes (6.3,5.8) using two families of sextupoles. The beta and dispersion functions are strongly perturbed for off-momentum cases.

produced by injecting $\tilde{1}000$ particles with different amplitudes up to a maximum emittance of 480 $\pi$ mm mrad and five different momentum spreads ($\delta p/p = 0, \pm 0.1, \pm 0.15$). Small field errors in the quadrupoles and dipoles were included, in the $10^{-}-4$ level. Finally, quadrupole fringe fields were simulated like "hard-edge" kicks at the entrance and the excite of the magnets.

The two maps correspond to two different cases: on the left the chromaticity sextupoles are switched off and the machine has its natural chromaticities $(\xi_x, \xi_y) = (-7.7, -6.4)$. Thus, there is a huge tune-spread of the order of 0.3 associated with of off-momentum particles motion. In addition, the quadrupole fringe-fields produce an "octupole-like" tune-shift linear with amplitude, which corresponds to the triangular shape of the foot-prints. This tune-shift pushes large amplitude off-momentum particles into dangerous resonances, as the structural coupling resonances in the middle of the plot $Q_x + Q_y = 12$. This resonance can be excited by linear coupling errors due to magnet tilts and misalignments [8]. Moreover this line corresponds to an octupole resonance of the type $2Q_x + 2Q_y = 12$ which can be excited by the quadrupole fringe-fields. The detrimental effect of this resonance is reflected in the irregularity of the map at bottom corner of the plot corresponding to particles with momentum spread of $\delta p/p = 0.15$.

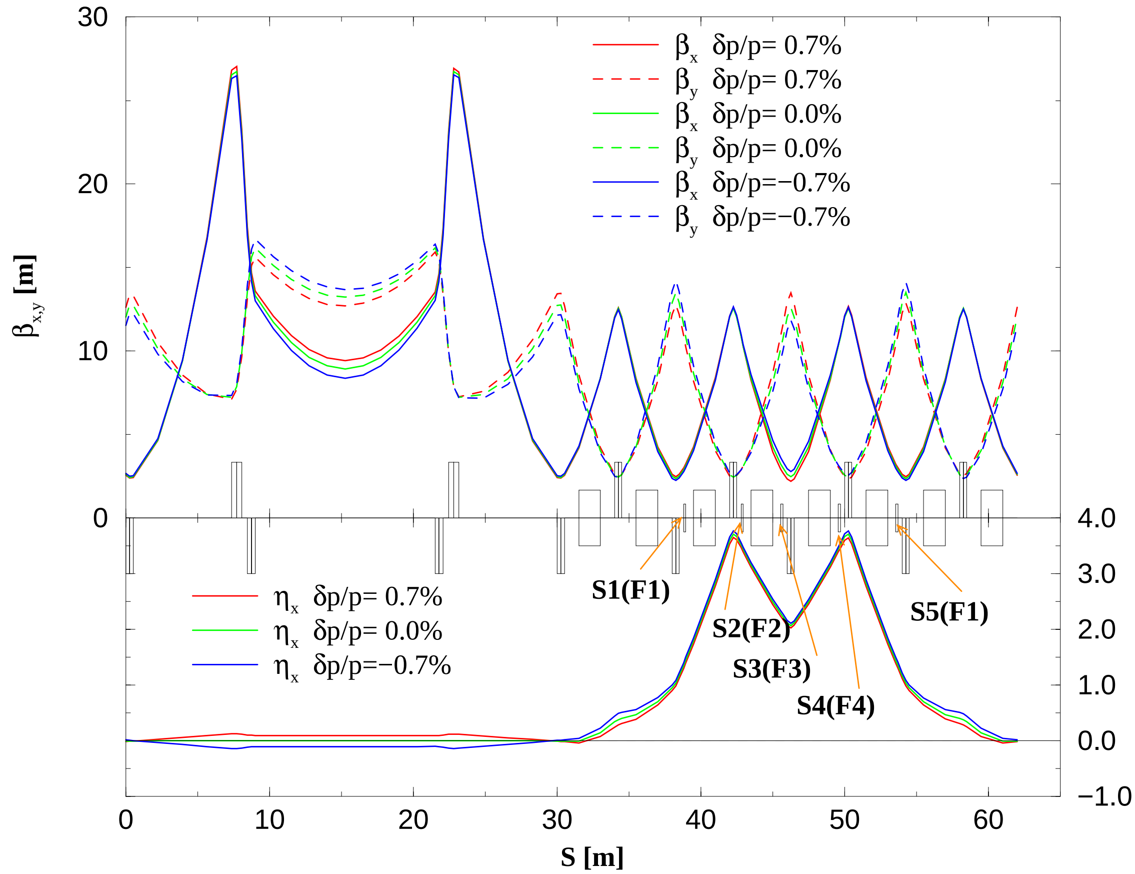


Figure 4: Lattice functions of the SNS accumulator ring for the nominal tunes (6.3,5.8) using 4 families of sextupoles. The beta and dispersion wave has been minimized by the introduction of the 2 supplementary sextupole families.

The map on the right corresponds to a case where the sextupoles are tuned in order to set the chromaticities to 0. As expected, the chromatic tune spread is eliminated.

The detrimental effect of the natural chromaticity can be further observed in the dynamic aperture of the SNS ring. In Figs. 7, we plot the maximum survival amplitude (in terms of total emittance) of particles launched in 5 different initial ratios of the transverse emittances, with three different momentum spreads ($\delta p/p = 0, \pm 0.2$). The momentum spread of $\pm 0.2$ is indeed higher than the actual RF bucket size of $\pm 0.7$. Nevertheless, it corresponds to the momentum acceptance of the ring and halo particles can reach this level before they are "cleaned" by the Beam-In-Gap kicker. By Figs. 7, one may observe the unacceptable reduction in the dynamic aperture of the SNS ring below the physical aperture of 180 $\pi$ mm mrad for a momentum spreads of -0.2 (green curve on the left). This is attributed to the fact that the chromaticity pushes the particles' vertical tune towards the very dangerous integer resonance, at $Q_y = 6$ and the particles get rapidly lost. A less pronounced reduction of the dynamic aperture can be attributed to the half-integer resonance at $2Q_y = 11$ for particles with momentum spread of 0.2 (red curve on the left). Finally, the on momentum particles have very similar dynamic

Table 1: Sextupole magnet parameters for the proposed hybrid lattice SNS ring.

| Quantity | Value | unit |
|---|---|---|
| Sextupole: | | |
| Regular ring sextupole: | | |
| number | 12 | |
| magnetic length | 0.30 | m |
| magnetic strength, $B''/B\rho$ | 4.15 | $m^{-3}$ |
| magnetic gradient | 23.5 – 28.1 | $T/m^2$ |
| pole inscribed diameter | 21 | cm |
| peak field at pole tip | 0.13 – 0.16 | T |
| Large ring sextupole: | | |
| number | 8 | |
| magnetic length | 0.30 | m |
| magnetic strength, $B''/B\rho$ | 4.15 | $m^{-3}$ |
| magnetic gradient | 23.5 – 28.1 | $T/m^2$ |
| pole inscribed diameter | 26.4 | cm |
| peak field at pole tip | 0.21 – 0.25 | T |

aperture (blue curves).

One should stress that the effects mentioned above are somehow independent of the working point choice due to the big chromaticity tune-spread. Actually, complementary studies for the working points (6.23,5.24) and (6.40,6.30) produce equivalent results, further demonstrating the absolute necessity for the inclusion of the chromaticity sextupoles in the baseline design of the SNS ring lattice. Furthermore, all the studies above have been conducted in the absence of space-charge effects, whose non-linear nature can further enhances particle diffusion. Let us finally note that the need of chromaticity control will be necessary from the early stages of the commissioning procedure, as, for low intensities, it will be the dominant tune-spread effect.

#### 2.2.2 Resonance effect induced by chromaticity sextupoles

The introduction of non-linear elements as chromatic sextupoles can perturb the motion of particles in the ring. By using classical perturbation theory, we can show that sextupoles introduce a second order (quadratic in the sextupole strength) tune-shift with amplitude which is linear with the particles' emittance, equivalent to a first order octupole effect. This tune-shift may be quantified by the anharmonicity coefficients, $a_{hh} = dQ_x/d\varepsilon_x$, $a_{vv} = dQ_y/d\varepsilon_y$ and $a_{hv} = dQ_x/d\varepsilon_y$, the first derivatives of the tune with respect to the emittance. These three quantities have been computed for all range of chromaticity values and plotted Fig. 8. The maximum anharmonicity values are found to be a factor of five smaller than the ones introduced by the quadrupole fringe-fields [7], indicating that the introduction of chromatic sextupoles will not have an important non-linear impact on the SNS ring. This residual octupole-like tune-shift can be corrected by dedicated octupole correctors [7].

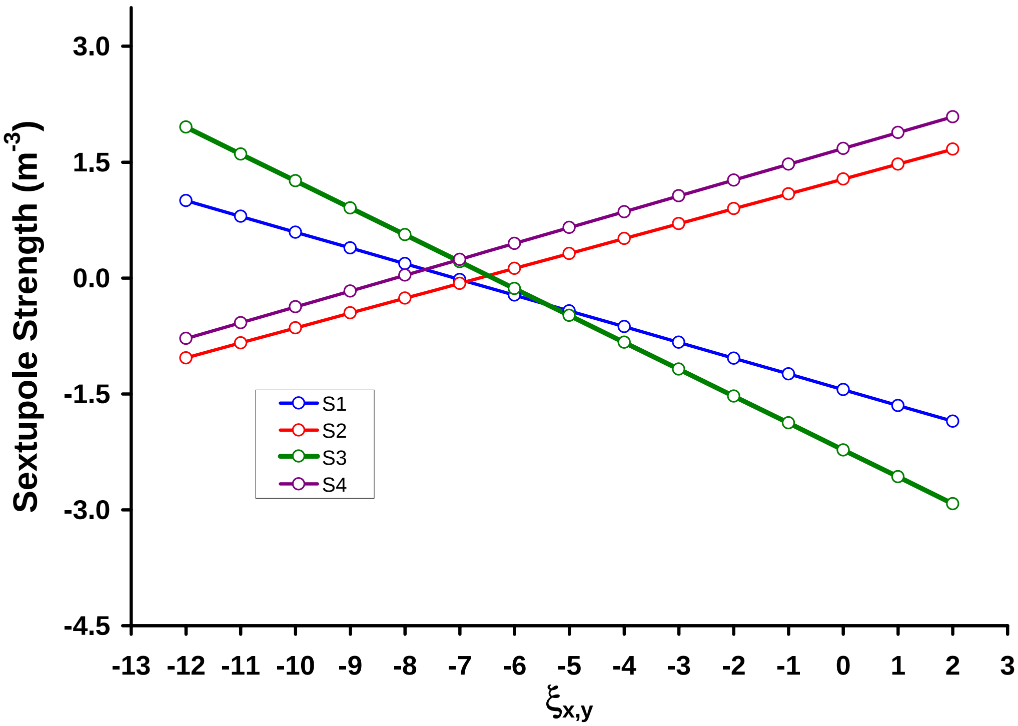


Figure 5: Sextupole strengths for the four families of chromatic sextupoles versus the chromaticity. The maximum values are within the strength requirements (Table 2.1).

On the other hand, the sextupoles may excite sextupole type of resonances defined by the condition $3Q_x = N$ or $Q_x \pm 2Q_y = N$ where $N$ is an integer number. In the case of the SNS ring, the excitation of these resonances due to the chromaticity sextupoles is quite small [2] and can be corrected with the dedicated sextupole correctors downstream of the quadrupoles, at the beginning of the arc (SVX1, SHX2, see Fig. 1).

# 3 Impact on Ring cost and Schedule

The impact on the construction schedule for both the sextupoles and trim quadrupole elements is insignificant. The total unburdened cost for the twenty chromatic sextupoles mechanical part is \$ 770,399 [9]. The cost for the electrical part of the chromatic sextupoles, i.e. four 600 A power supplies (three of 40 KW/67 V and 1 of 70 KW/117 V), cables and controls is \$ 570,357 [10].

# 4 Summary

The SNS accumulator ring is designed to accumulate a high-intensity beam, with large transverse emittance of 160 $\pi$ mm mrad. With the required low beam loss level of $10^{-4}$, the machine is designed in such a way to avoid any undesirable non-linear effects and instabilities which can

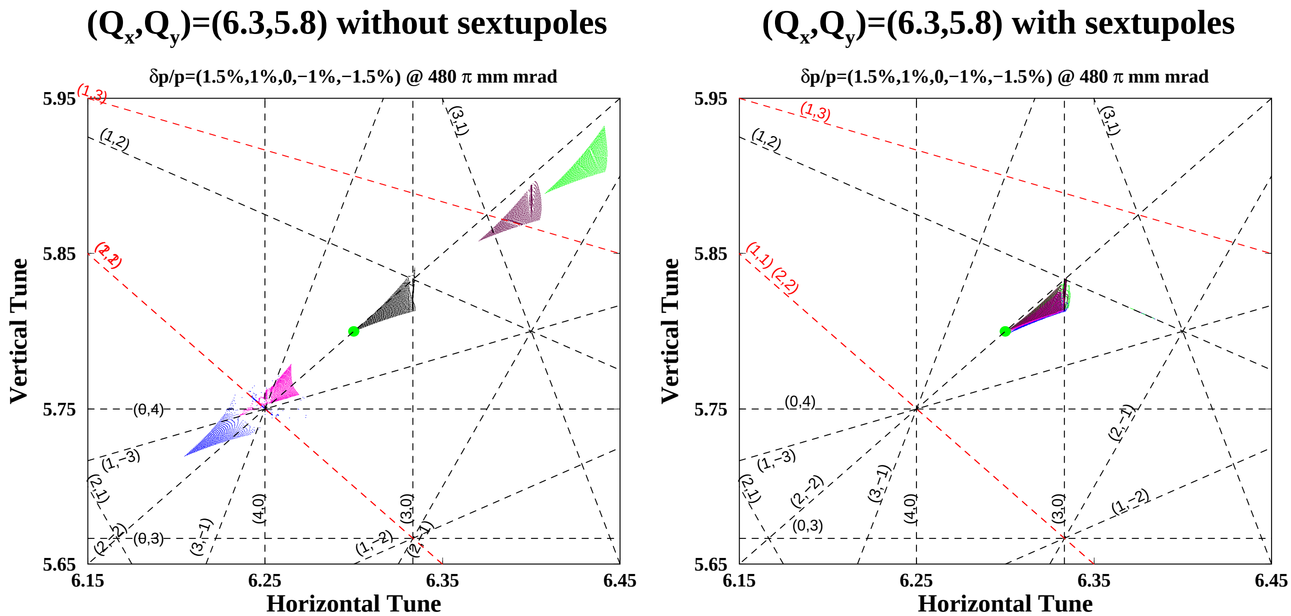


Figure 6: Frequency maps for the working point (6.3,5.8), without (left) and with (right) sextupoles.

limit its performance. The chromaticity control is one of the main issues in order to achieve this goal. Four families of sextupoles are needed in order to adjust the chromaticity and to keep the optical properties of the ring unperturbed. The required sextupole' strengths can be easily achieved with the proposed design properties of these magnets. The impact of these magnets with respect to non-linear dynamics is expected to be small and can be corrected with the dedicated multi-pole correctors of the SNS ring.

# 5 Acknowledgments

We would like to thank Joe Tuozollo, Bob Lambiase, George Mahler and Ioannis Marneris for many usefull discussions regarding engineering issues. We would like also to thank Kerry Mirabella for her assistance in the cost estimates.

# References

[1] J. Wei, *et al.*, BNL/SNS Technical Note 76, 2000.

[2] N. Tsoupas, *et al.*, Proc. EPAC'00, Vienna, 2000.

[3] C.J. Gardner, BNL/SNS Technical Note 37, 1997.

[4] H. Grotte and C. Iselin, *"The MAD Program Version8.19, User's Reference Manual"*, CERN/SL/90-13(AP) - Rev.5, 1996.

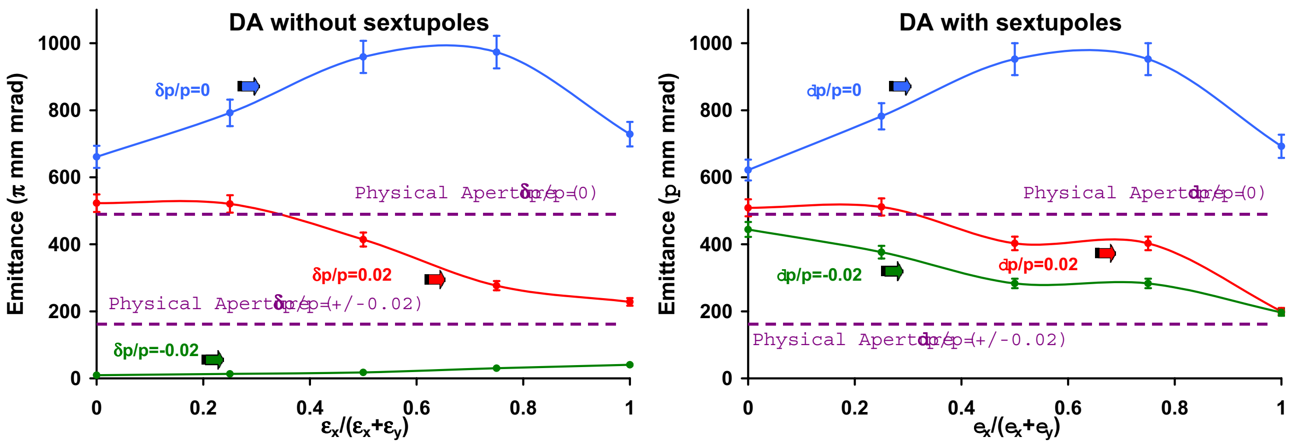


Figure 7: Dynamic aperture for the working point (6.3,5.8), without (left) and with (right) sextupoles.

[5] J. Laskar, Physica D 67, 257 (1993); J. Laskar and D. Robin, Part. Acc. 54, 183 (1996).

[6] Y. Papaphilippou, Proc. PAC'99, New York, 1999.

[7] Y. Papaphilippou and D.T. Abell, Proc. EPAC'00, Vienna, 2000.

[8] A.V. Fedotov, *et al.*, ICAP'00 Proceedings, Darmstadt, Germany, September 2000; A.V. Fedotov, *et al.*, BNL/SNS Technical Note 86, 2001.

[9] J. Tuozzolo, Private Communication.

[10] R. Lambiase and I. Marneris, Private Communication.

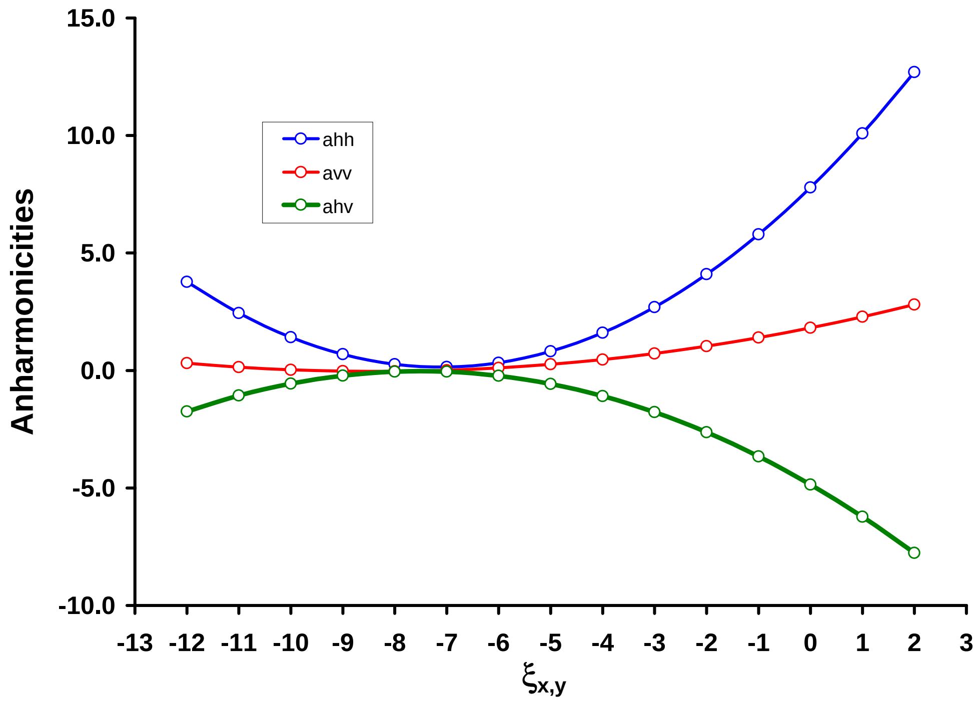


Figure 8: Anharmonicities versus the chromaticity. The maximum values are within 5% of the ones produced by the quadrupole fringe-fields.